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Influence of alloying elements on the laser cutting process

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Abstract

This paper presents an experimental investigation into how different alloying elements affect the laser-oxygen cutting process. Small variations in chemical composition of the material can lead to major changes in the overall laser-oxygen cutting process. The changes can appear as differences in cut edge roughness and/or adherent dross on the bottom of the cut. The primary causes of the process sensitivity have been identified as changes in surface tension and viscosity of the molten material in combination with changes in the exothermal reaction in the cut zone.

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1. Introduction

Laser cutting is a well-established profiling method in industry, and has been so for at least three decades. A variety of materials, from wood to super alloys, can be cut by this process. One of the main materials to be laser cut though is steel, which is done in within large companies to relatively small job shops.

Laser cutting as a process can be divided into four different cutting mechanisms; Fusion cutting, Oxidation cutting, Chemical degradation and Vaporization.

This paper investigates the laser-oxygen cutting process of steel with different chemical composition. In this process the focused laser beam is used in conjunction with a pressurized jet of oxygen as shown in fig. 1. The high cutting rates achievable by this process are a result of the dual nature of the energy input from; the focused laser energy

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and the exothermic reaction of the metal with oxygen.

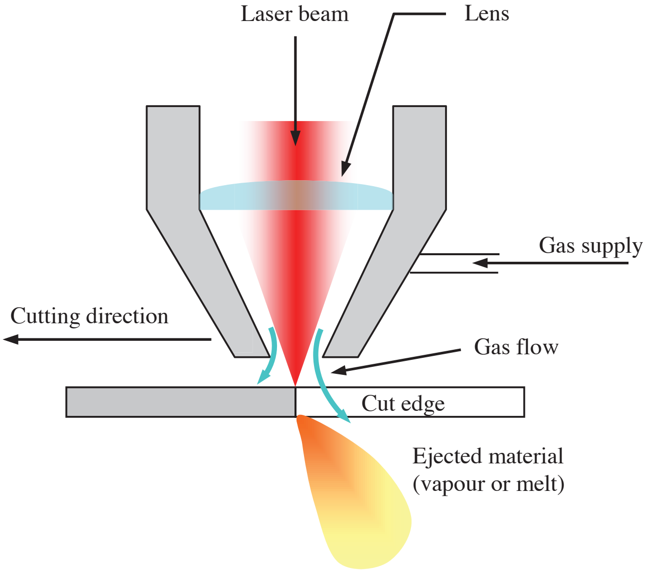


Fig. 1.A schematic of the cutting mechanism.

The use of oxygen as a cutting gas when profiling low alloyed steels has two important effects in the cut zone; the exothermic reaction of Iron with Oxygen generate a great deal of heat and, the molten oxides produced in the cut zone do not adhere well to the surrounding solid steel and therefore a clean cut edge is generated, see fig. 2.

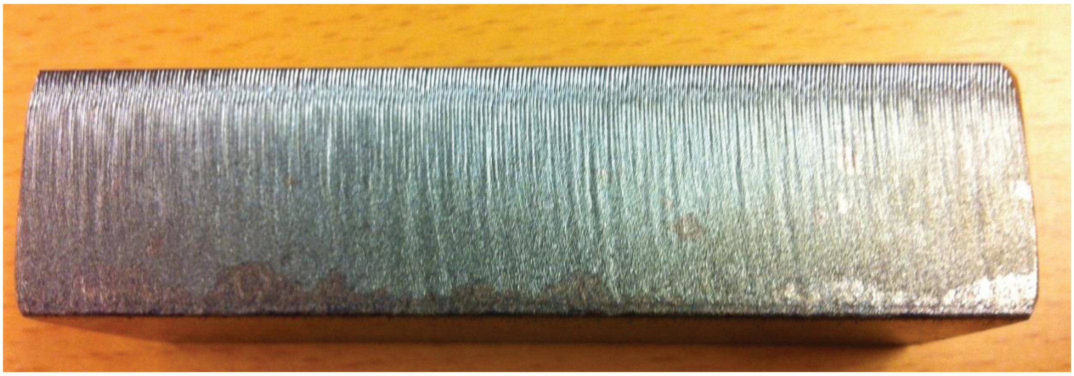


Fig. 2.A typical cut edge generated in low alloyed steel (20 mm) cut by a CO_2 laser in conjunction with an Oxygen jet.

Earlier work by the authors, Ivarson et al. (1991), Ivarson et al. (1992), Powell (1993) and Ivarson (1993), has shown that the heat generated by the oxidation of iron contributes approximately half of the energy input to the cut zone, and the laser supplies the remaining half. It has also been shown previously that half of the iron that leaves the cut zone is oxidized to FeO. Further, the cut front temperature is approximately 2000 K and at this temperature the heat generated by the oxidation reaction is $\Delta H = -257$ kJ/mol, Barin et al. (1973).

The cutting process can be described as a laser initiated oxidation reaction the products of which are ejected from the cut zone by the incident gas jet.

This paper is concerned with the surprisingly high sensitivity of the cutting process to small variations in the chemical composition of the material (low alloyed steel). This change in chemistry can have a detrimental effect on the cutting process which results in a rather poor cut edge quality. During this work the influence of three alloying elements was investigated: Carbon, Silicon and Manganese.

2. Experimental procedure

Seven laboratory steel plates were casted, each with an individual chemical composition that can be seen in table 1. These lab-plates were rolled to a thickness of 20 mm and the size of the plates is approximately 300x700 mm.

Table 1. Chemical composition of the lab-plates (wt %).

Sample	C	Si	Mn	Cr	Ni	Mo	Al
1	0.16	0.20	1.79	0.25	0.035	0.023	0.030
2	0.16	0.22	0.70	0.25	0.035	0.021	0.018
3	0.15	0.19	1.59	0.25	0.035	0.021	0.018
4	0.15	0.22	1.09	0.25	0.034	0.023	0.017
5	0.13	0.48	0.29	0.25	0.035	0.027	0.002
6	0.16	0.52	0.71	0.25	0.035	0.029	0.025
7	0.24	0.52	1.40	0.26	0.034	0.023	0.005

As can be seen out of table 1, the Silicon and Manganese content were changed in samples 1 to 6 and in sample 7 the Carbon, Silicon and Manganese content were changed. Since the plates were hot rolled in air, the surface of the plates had a mill scale. The laser cutting parameters used in this test can be seen in table 2.

Table 2. Laser cutting parameters.

Parameter	
Laser power	3000 W
Lens focal length	7.5 inch
Oxygen pressure	0.75 bar
Nozzle diameter	2.5 mm
Nozzle-material standoff	1.0 mm
Cutting speed	0.85 m/min

During the cutting trials, squares with a size of 50x50 mm were cut out, see fig. 3. The distance between the parts was 20 mm, i.e. in accordance with the normal recommendations (distance equal to material thickness). The parts were cut in cold condition which means that the plate had room temperature.

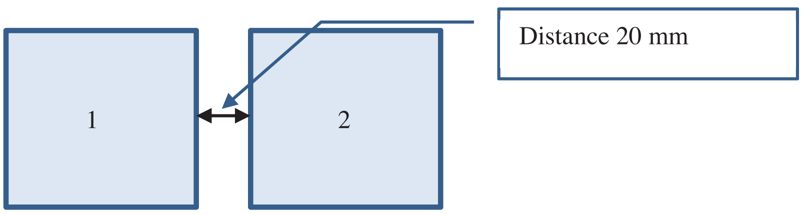


Fig. 3.Schematic of the parts cut out, 50x50 mm.

The cut examination was observed optically. The main points of interest being: a) the roughness of the cut edge and b) the presence of dross on the cut edge.

3. Results

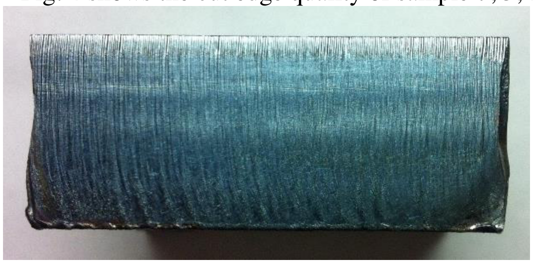
From the cutting tests the cut edge quality were ranked from 1 (best) to 7 (worst). Table 3 shows the ranking and also the content of Carbon, Silicon and Manganese.

Table 3. Cut edge quality ranking of different materials

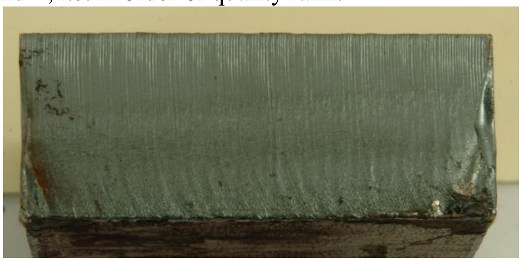
Quality rank	Sample	C (wt %)	Si (wt %)	Mn (wt %)
1	7	0.24	0.52	1.40
2	5	0.13	0.48	0.29
3	6	0.16	0.52	0.71
4	2	0.16	0.22	0.70
5	3	0.15	0.19	1.59
6	1	0.16	0.20	1.79
7	4	0.15	0.22	1.09

Table 3 shows that as the Silicon content does not affect the cut edge quality. On the other hand it seems that an increased amount of Manganese has a detrimental effect on the cut edge quality. Further, if the Carbon content is increased the cut edge quality is good although a high Manganese content.

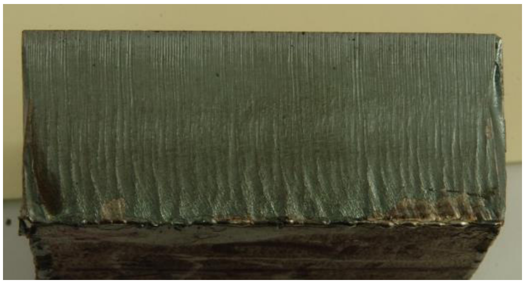
Fig. 4 shows the cut edge quality of sample 7, 5, 1 and 4, i.e. in order of quality rank.



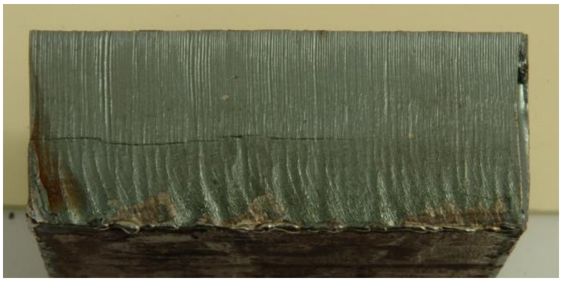
Sample 7, quality rank 1



Sample 5, quality rank 2



Sample 1, quality rank 6



Sample 4, quality rank 7

Fig. 4. Cut edge quality of sample 7, 5, 1 and 4.

As shown in fig. 4, the roughness of the lower part of the cut edge changes with increasing Manganese content if the Carbon content is low. If the Carbon content is increased (sample 7) the cut edge is rather smooth although a high Manganese content.

4. Discussion

As mentioned in the result section, the Silicon content does not seem to influence the cut edge quality. Samples with high Silicon content are top quality ranked and samples with low Silicon content show a rough cut edge and adherent dross. Increased amount of Manganese seems to affect the cut edge quality in a negative manner. Further, by increasing the Carbon content and still have a high Manganese and Silicon content, the cut edge quality is smooth and no adherent dross on the lower side of the cut.

It is mentioned in the introduction that laser-oxygen cutting of steel, approximately half the energy to the cut zone is generated by the exothermal reaction of Iron and Oxygen (remaining half is supplied by the laser). Of course, Oxygen reacts with other alloying elements as well, and the order of oxidation at 2073 K is the following:

1. $C + 1/2O_2 \rightarrow CO$ $\Delta H_{298} = -110.5$ kJ/mol
2. $Si + O_2 \rightarrow SiO_2$ $\Delta H_{298} = -910$ kJ/mol
3. $Mn + 1/2O_2 \rightarrow MnO$ $\Delta H_{298} = -385.2$ kJ/mol
4. $C + O_2 \rightarrow CO_2$ $\Delta H_{298} = -400$ kJ/mol
5. $2Cr + 3/2O_2 \rightarrow Cr_2O_3$ $\Delta H_{298} = -1130$ kJ/mol
6. $Fe + 1/2O_2 \rightarrow FeO$ $\Delta H_{298} = -266.3$ kJ/mol

Out of the result and the chemical reactions above the following oxides are of interest: CO, MnO and FeO. Silicon and SiO_2 is not of interest according to the result/discussion above. CO_2 is not of interest due to that all Carbon has already been oxidized in the CO reaction.

Chromium oxide is not of interest since it is the same for all samples and its melting point is too high (above the temperature of the cut zone). Further, if Chromium should oxidize its oxidation energy is high and this should result in sporadic burning on the cut edge, i.e. a rough cut edge surface.

Changing the relationship between Carbon and Manganese, the chemical thermodynamics in the cut zone will change. By increasing the amount of Carbon and at the same time reduce the amount of Manganese, the exothermal energy will be reduced. This results in a more stable cutting process, with reduced risk of sporadic burning (i.e. reduced risk of a rough cut edge). This is, at present stage, the most reasonable explanation why material with high Manganese content is cut with a poor cut edge quality compared to a material cut with a low Manganese content (all other alloying elements constant).

At the same time, decreasing the exothermal energy, the temperature of the cut front will decrease and as a result the viscosity and surface tension of the molten material will increase. This, however, does not seems to be a problem from a dross attachment point of view. This phenomenon might be studied separately in the future.

5. Conclusion

The experimental investigation in laser cutting material with different content of Carbon, Silicon and Manganese can be concluded as follows:

- The Silicon content does not seem to affect the cut edge quality, i.e. samples with high Silicon content show high quality cut edges.
- Increase Manganese content reduces the cut edge quality, i.e. a rough cut edge quality with adherent dross on the lower side of the cut.
- Carbon seems to stabilize the laser cutting process. Increased Carbon content reduces the overall exothermal reaction if the Manganese content is high.

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